



Calibration and validation of model describing complete autotrophic nitrogen removal in granular sludge

Vangsgaard, Anna Katrine; Mutlu, A. Gizem; Gernaey, Krist; Smets, Barth F.; Sin, Gürkan

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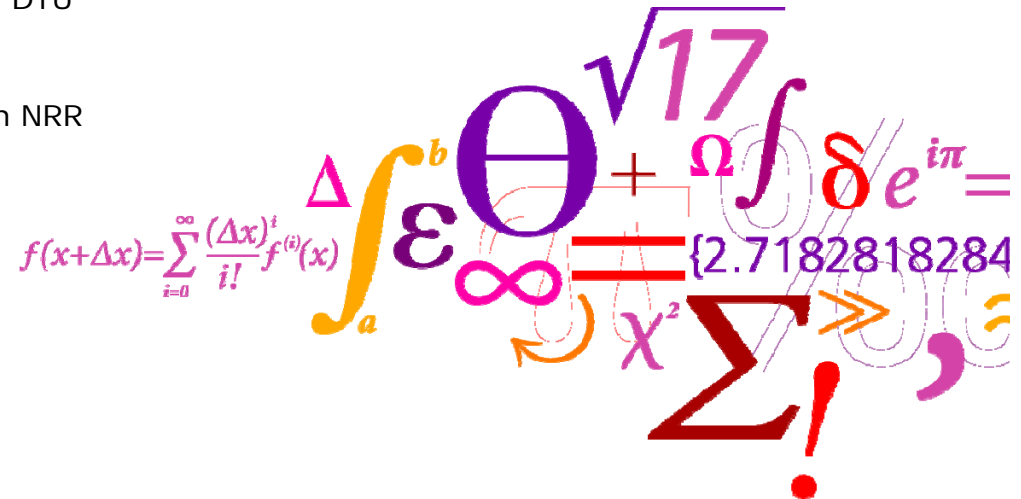
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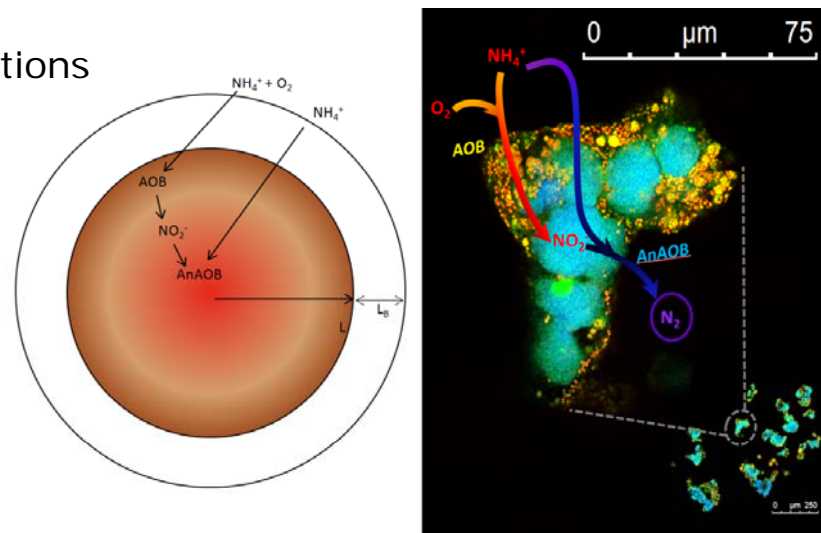
The case

A granular sludge SBR performing N removal through nitrification/anammox

- Calibration methodology developed
- Fast model initialization
- Stoichiometric ratio evaluation

Purpose:

- Experiment planning
- Performance prediction for control applications



Methods

Physical system

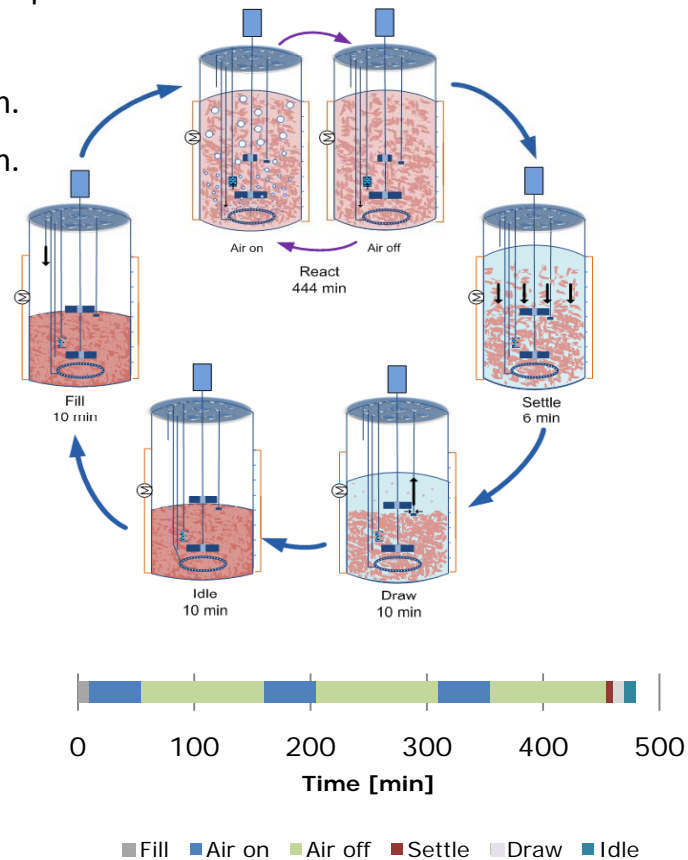


Reactor characteristics:

Volume:	4L
Temperature:	30°C
pH:	7.5 ± 0.3
Mixing:	6-bladed Rushton impeller at 80 rpm + bubble aeration
Solids concentration:	4.2 g VSS/L
Ave. gran. size:	50 µm
Operating time:	11 months

Sequencing batch operation:

Fill:	10 min.
Reaction:	444 min. consisting of three aerated phases and three non-aerated phases
Settling:	6 min.
Draw:	10 min.
Idle:	10 min.



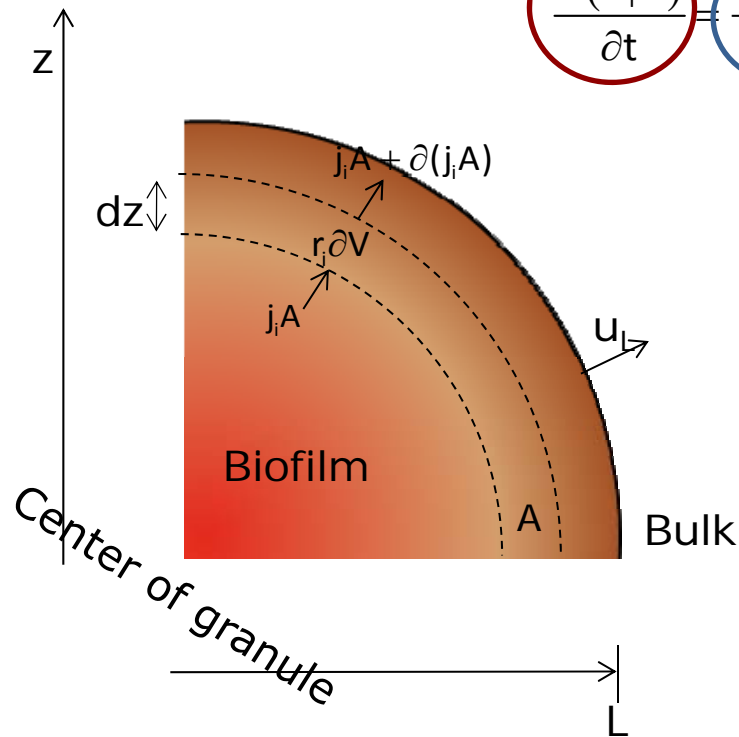
Methods

Model description

Biofilm mass balance equations – Transport and microbial metabolism

$$\text{Accumulation} = \text{Inflow} - \text{Outflow} + \text{Generation} - \text{Consumption}$$

$$\frac{\partial(C_i V)}{\partial t} = -\partial(j_i A) + r_i \partial V \quad \Leftrightarrow \quad \frac{\partial C_i}{\partial t} = \frac{1}{z^2} \frac{\partial}{\partial z} (z^2 j_{ci}) + r_i$$



1. Transport of **soluble** compounds is governed by **diffusion** and of **particulate** compounds by **advection**:

$$j_{si} = D_{bio,i} \frac{\partial S_i}{\partial x} \quad j_{xi} = -X_i u_F$$

2. The **granule radius** is a function of the growth and decay of bacteria and a detachment process:

$$\frac{dL}{dt} = u_{F,L} - u_D$$

Where the advective velocity is a function of the growth of particulates on the "inside" of a given point k:

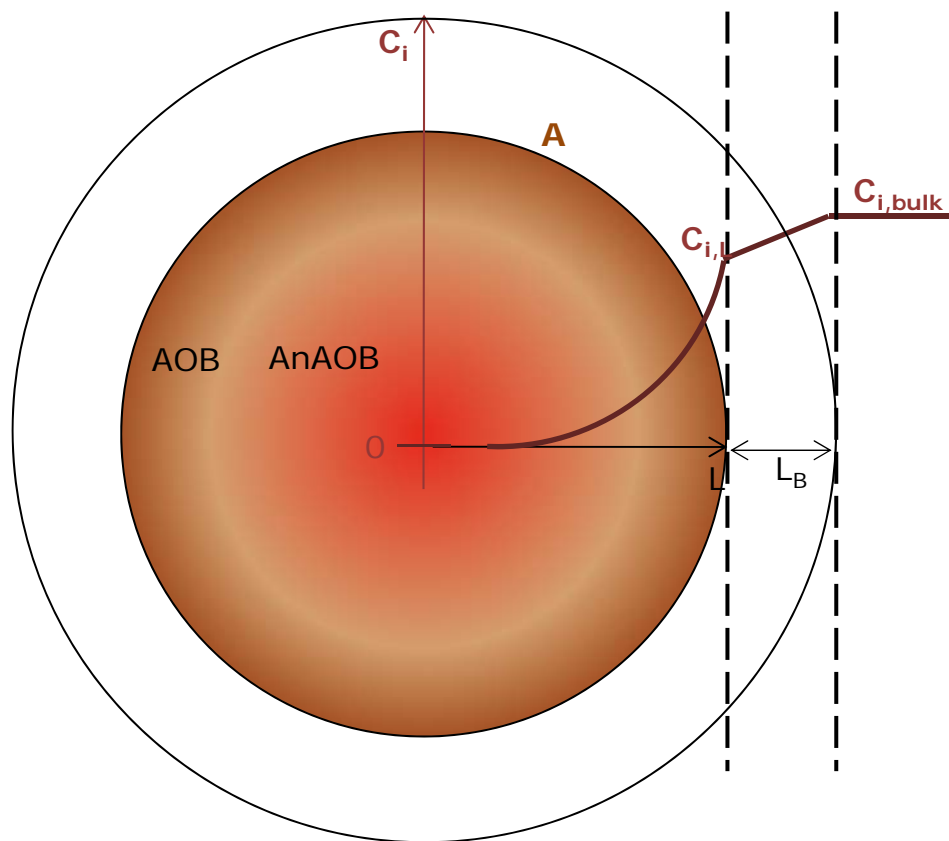
$$u_{F,k} = \frac{1}{A_k} \int_0^k A_k \left(\sum_{i=1}^{n_{part}} \frac{r_i}{\rho} \right) dz$$

Methods

Model description

Bulk liquid mass balance equations – Transport and microbial metabolism

$$\text{Accumulation} = \text{Inflow} - \text{Outflow} + \text{Generation} - \text{Consumption}$$



$$\frac{dC_i}{dt} = \frac{Q_{in} C_{i,in} - Q_{out} C_{i,bulk} - j_{Ci} A}{V} + r_{Ci}$$

Flux in and out of the biofilm:

Soluble species

$$j_{Si} = k_i (S_{i,bulk} - S_{i,L})$$

where

$$k_i = \frac{D_i}{L_B}$$

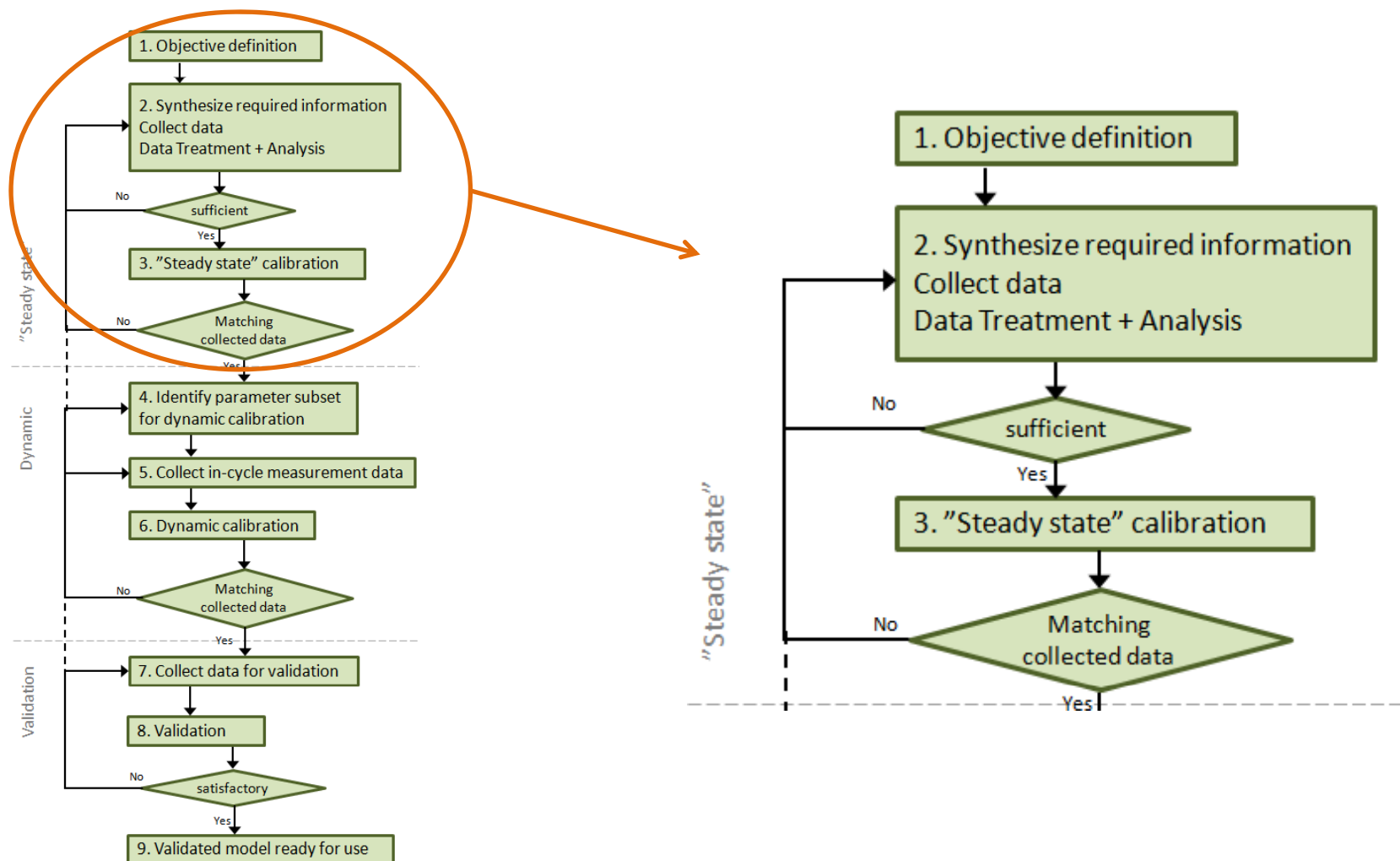
Particulate species

$$j_{Xi} = -u_D X_{i,L}$$

The mass transfer coefficient is estimated from a semi-empirical correlation considering mixing caused by bubble aeration

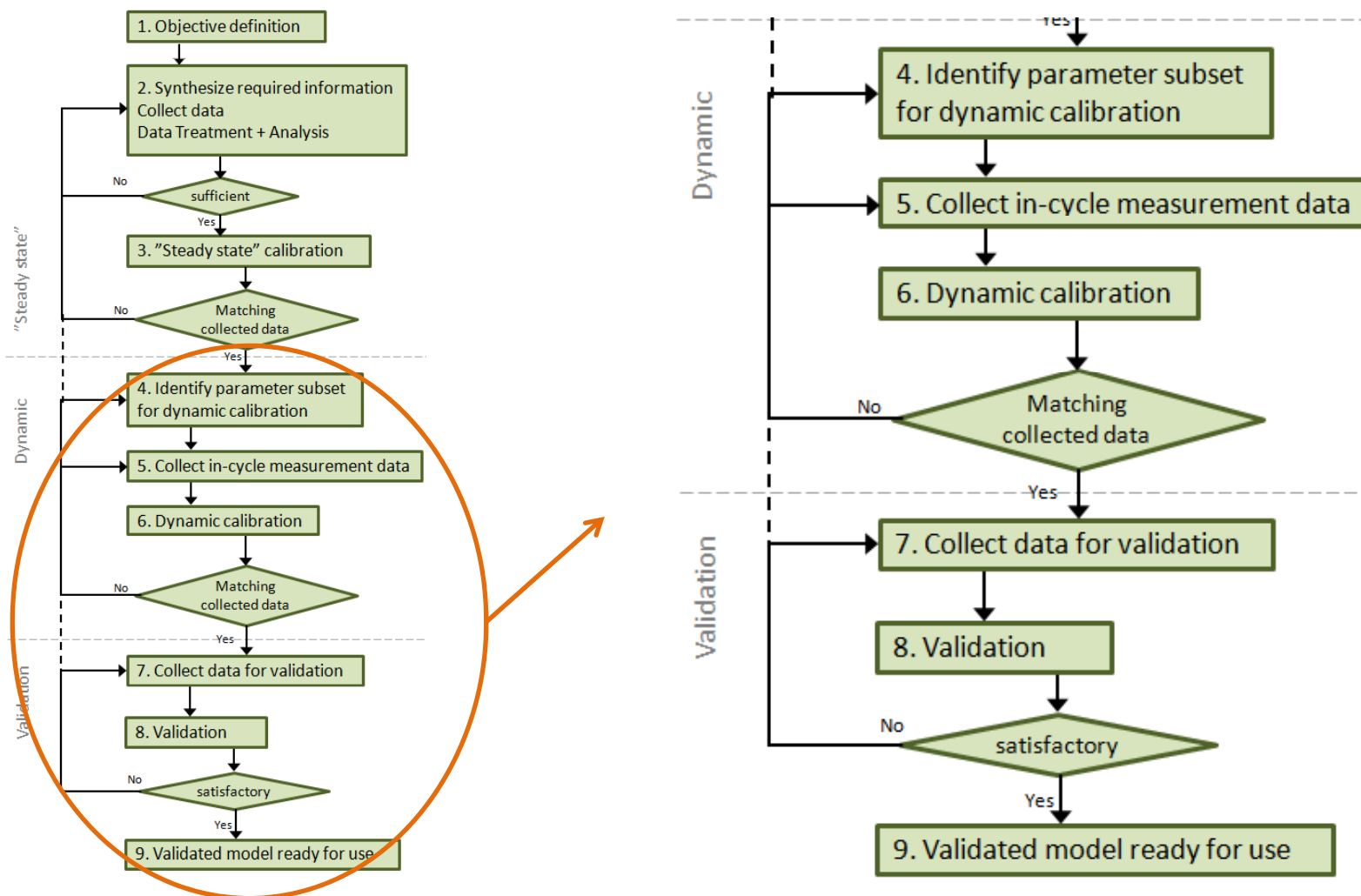
Methods

Methodology development



Methods

Methodology development



Results

Steady state calibration

- Step 1:
Determine bulk liquid soluble N species concentrations

- Step 2:
Capturing overall reactor performance through five evaluation criteria:
Three ratios and two efficiencies:

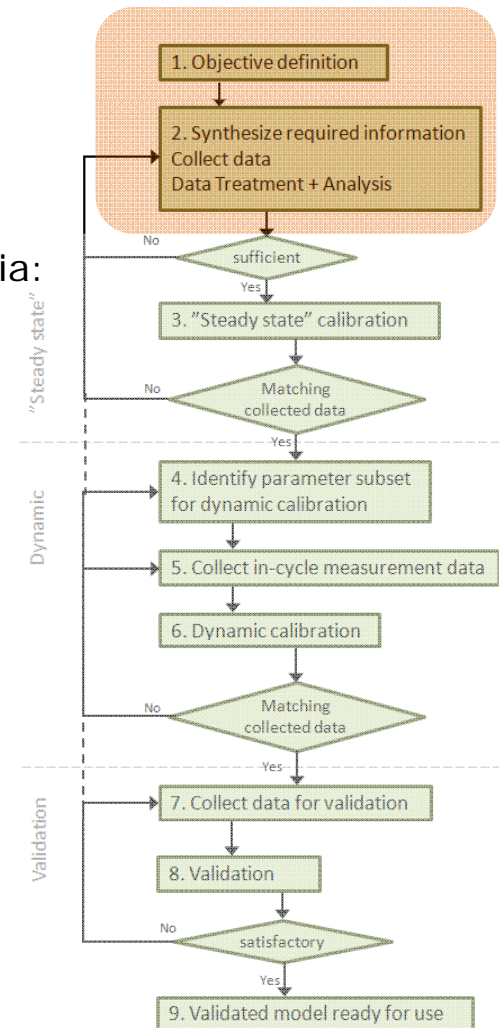
$$R1 = \frac{\Delta \text{NO}_2^-}{\Delta \text{NH}_4^+} \longrightarrow \text{AOB vs. AnAOB} + \text{NOB} \rightarrow \text{relative activity}$$

$$R2 = \frac{\Delta \text{NH}_4^+}{\Delta \text{TN}} \longrightarrow \text{AnAOB vs. AOB} \rightarrow \text{relative activity}$$

$$R3 = \frac{\Delta \text{NO}_3^-}{\Delta \text{NH}_4^+} \longrightarrow \text{AnAOB vs. NOB} \rightarrow \text{relative activity}$$

$$E1 = \frac{\Delta \text{NH}_4^+}{\text{NH}_{4,\text{in}}^+} \longrightarrow \text{Absolute microbial activity}$$

$$E2 = \frac{\Delta \text{TN}}{\text{TN}_{\text{in}}} \longrightarrow \text{Absolute microbial activity}$$



Results

Steady state calibration

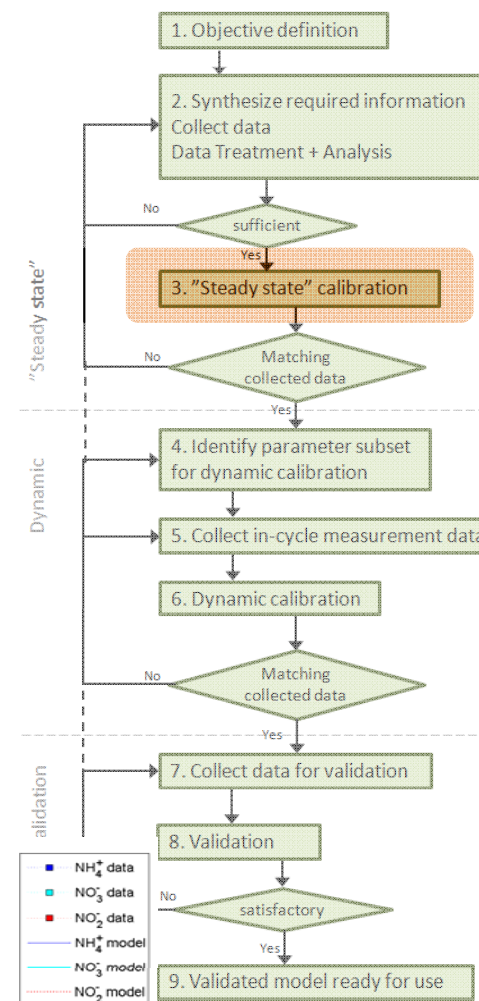
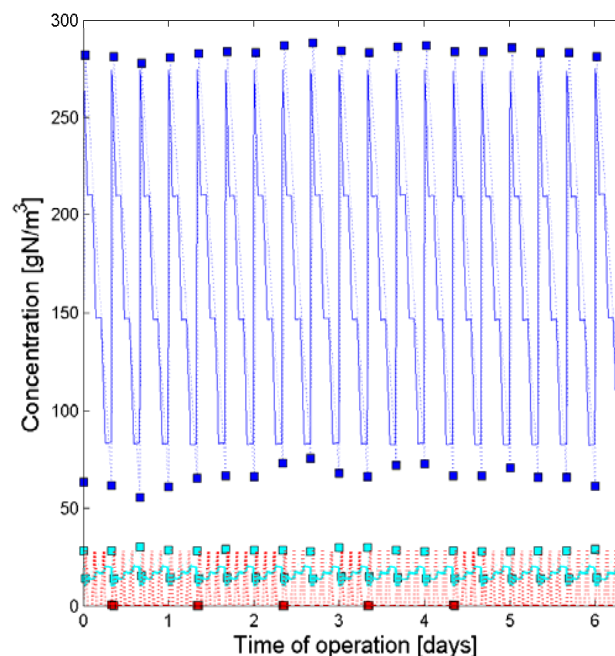
- Step 3:

Since oxygen $k_L a$ could not be experimentally estimated, this was calibrated based on the five evaluation criteria:

	$k_L a$ d^{-1}	R1 $\Delta NO_2^- / \Delta NH_4^+$	R2 $\Delta NH_4^+ / \Delta TN$	R3 $\Delta NO_3^- / \Delta TN$	NH_4^+ removal %	TN removal %
Simulation	524.4	0.000	1.052	0.049	79.25	74.32
Experimental	-	0.001	1.072	0.071	80.80	71.52

Experimental values were obtained as an average of one week of "steady state" operation.

Model was initialized by simulating continuous operation for 1000 days, which was then followed by 10 days of SBR operation of which the results from the last cycle were used for the steady state model evaluation.



Results

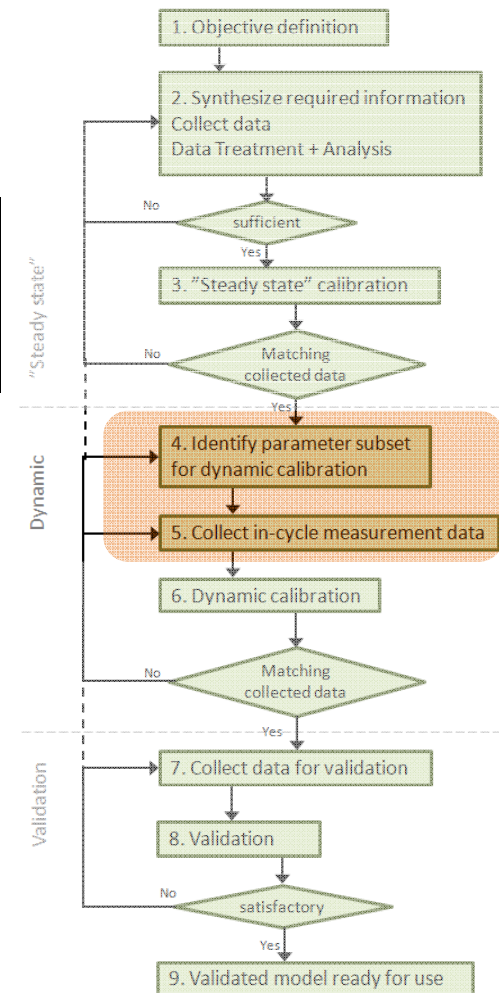
Dynamic calibration

- Step 4: Parameter subset identification
Based on global sensitivity analysis:

	$\mu_{\max, \text{AOB}}$ d^{-1}	$K_{\text{O}_2, \text{AOB}}$ gCOD/m^3	b_{AOB} d^{-1}	$\mu_{\max, \text{AnAOB}}$ d^{-1}	$K_{\text{O}_2, \text{AnAOB}}$ gCOD/m^3	Y_{AnAOB} gCOD/gN
Default value	2.050	0.300	0.130	0.073	0.010	0.160
Lower bound	1.538	0.150	0.098	0.055	0.005	0.152
Upper bound	2.563	0.450	0.163	0.091	0.015	0.168

- Step 5: In-cycle data collection

Samples from bulk liquid were manually collected every 15 min.
and analyzed for soluble N species.
Analysis results from three cycles were used for calibration.



Results

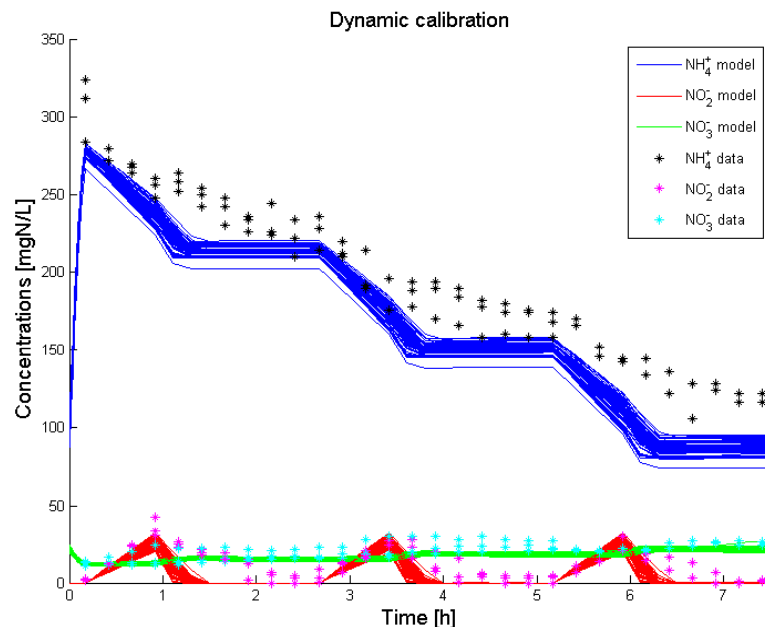
Dynamic calibration

- Step 6: Calibration

Based on pragmatic Monte Carlo method, which was evaluated by WSSE:

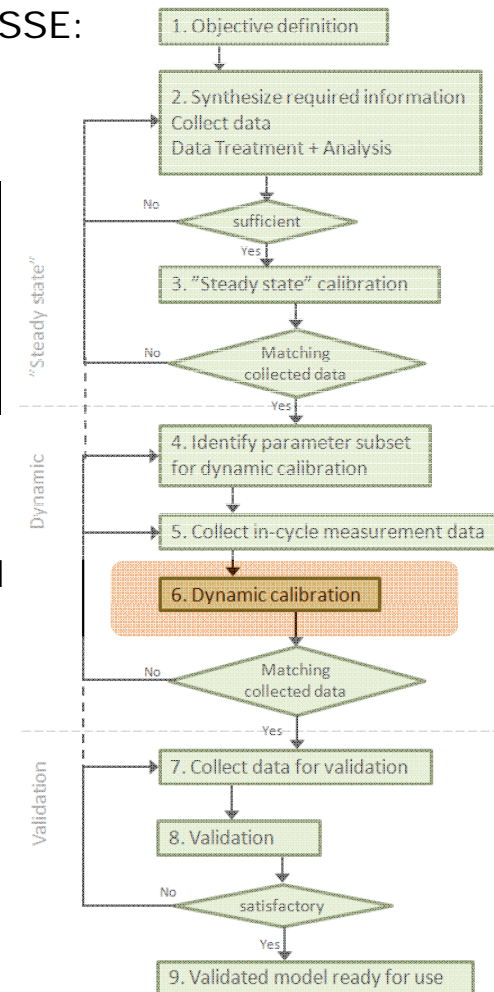
$$WSSE = \sum_{k=1}^m \sum_{i=1}^n \left(\frac{y_{meas,k}(t) - y_{model,k}(t, \theta)}{\sigma_k} \right)^2$$

	$\mu_{max,AOB}$ d^{-1}	$K_{O_2,AOB}$ $gCOD/m^3$	b_{AOB} d^{-1}	$\mu_{max,AnAOB}$ d^{-1}	$K_{O_2,AnAOB}$ $gCOD/m^3$	Y_{AnAOB} $gCOD/gN$
Default value	2.050	0.300	0.130	0.073	0.010	0.160
Lower bound	1.538	0.150	0.098	0.055	0.005	0.152
Upper bound	2.563	0.450	0.163	0.091	0.015	0.168
Calibrated value	2.450	0.165	0.136	0.068	0.011	0.166



However, all MC sims have an offset compared to the collected data

→ Iteration of step 4-6, in accordance with the methodology

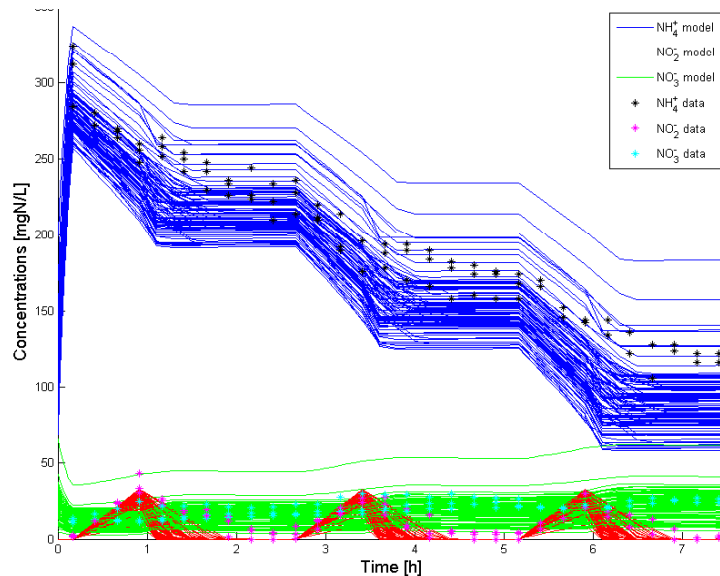


Results

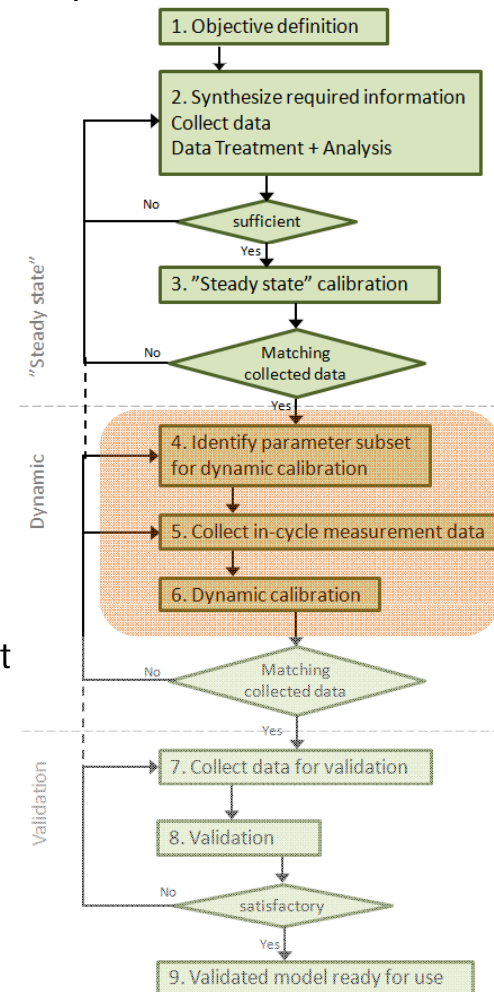
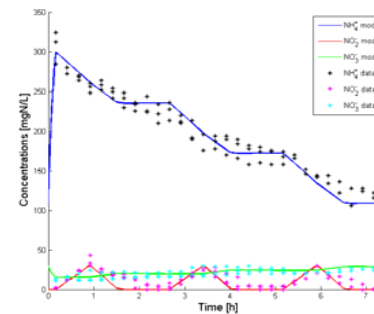
Dynamic calibration

- Step 4-6 - iterated: Parameter subset and sampling space were expanded

	Unit	Default value	Lower bound	Upper bound	Calibrated value
$\mu_{\max, \text{AOB}}$	d^{-1}	2.050	1.025	3.075	2.064
$K_{\text{O}_2, \text{AOB}}$	gCOD/m^3	0.300	0.150	0.450	0.332
b_{AOB}	d^{-1}	0.130	0.065	0.195	0.150
$\mu_{\max, \text{NOB}}$	d^{-1}	1.454	0.727	2.181	0.974
$K_{\text{O}_2, \text{NOB}}$	gCOD/m^3	1.100	0.550	1.650	0.752
b_{NOB}	d^{-1}	0.061	0.030	0.091	0.069
$\mu_{\max, \text{AnAOB}}$	d^{-1}	0.073	0.037	0.110	0.088
$K_{\text{O}_2, \text{AnAOB}}$	gCOD/m^3	0.010	0.005	0.015	0.013
$K_{\text{HNO}_2, \text{AnAOB}}$	gN/m^3	$2.81\text{e-}6$	$1.41\text{e-}6$	$4.22\text{e-}6$	$2.92\text{e-}6$
Y_{AOB}	gCOD/gN	0.210	0.105	0.315	0.292
Y_{AnAOB}	gCOD/gN	0.160	0.080	0.240	0.124
D_{NO_2}	m^2/d	$2.60\text{e-}4$	$1.30\text{e-}4$	$3.90\text{e-}4$	$1.70\text{e-}4$
L_{B}	m	$1.76\text{e-}5$	$8.80\text{e-}6$	$2.64\text{e-}5$	$2.26\text{e-}5$



Among the new MC sims, the subset sample giving the smallest error fitted much better to the data than the previous.



Results

Validation

- Step 7: Data collection for validation

Samples were collected during one cycle under slightly different conditions compared to the calibration cycles. The solids concentration was 4.4 g VSS/L and average granule size was 35 μm .

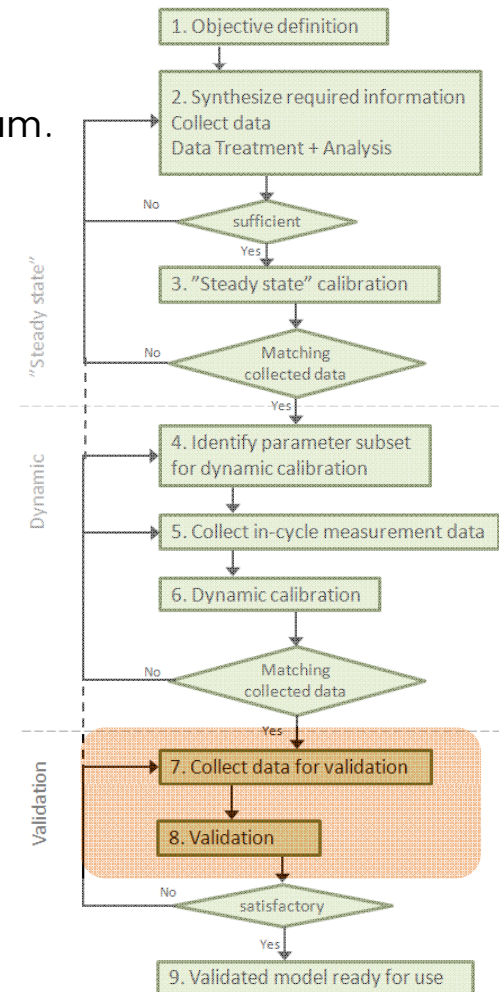
- Step 8: Validation

The validation was evaluated by the Janus coefficient:

$$J^2 = \frac{\frac{1}{n_{\text{val}}} \sum_{i=1}^{n_{\text{val}}} (y_{\text{meas},i} - y_{\text{model}}(t_i, \theta))^2}{\frac{1}{n_{\text{cal}}} \sum_{i=1}^{n_{\text{cal}}} (y_{\text{meas},i} - y_{\text{model}}(t_i, \theta))^2}$$

Model output	MAE		RMSE		Janus coefficient
	Calibration	Validation	Calibration	Validation	
NH_4^+	0.030	0.053	0.039	0.057	1.478
NO_2^-	0.265	0.116	0.366	0.173	0.473
NO_3^-	0.131	0.080	0.171	0.093	0.544

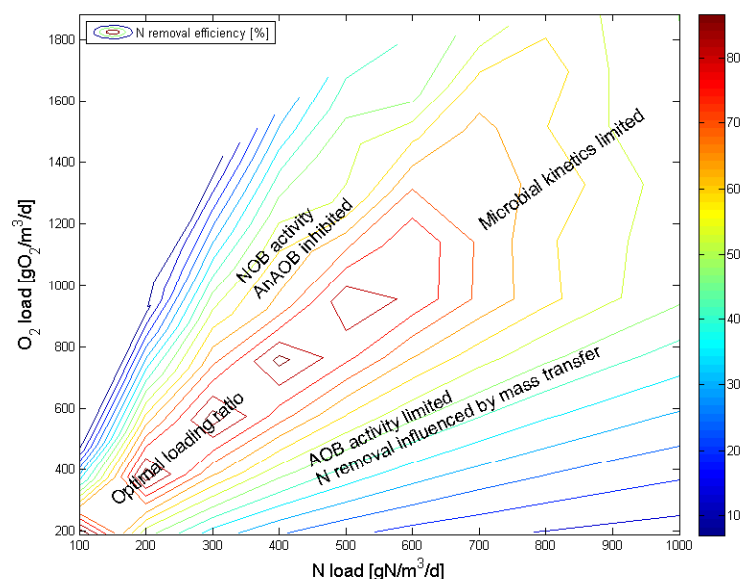
J is relatively close to 1 for all model outputs, which implies a good model fit.



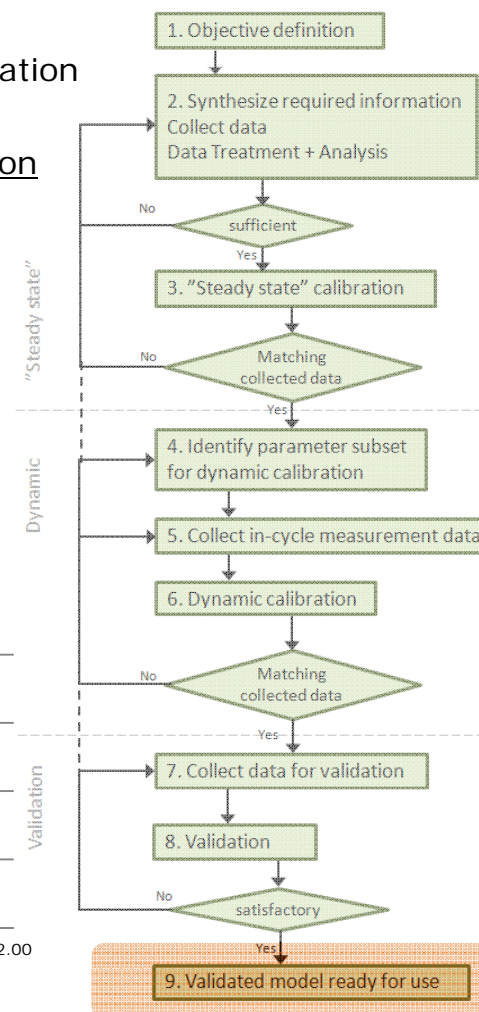
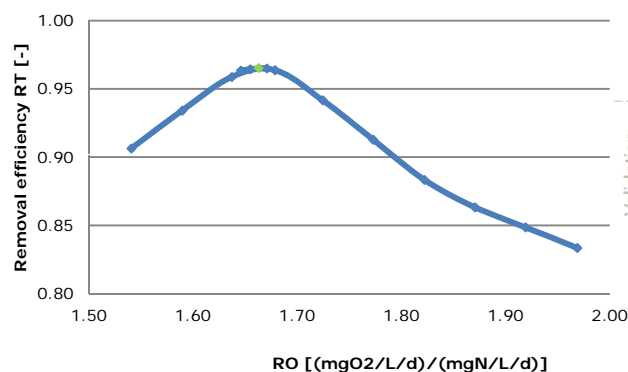
Perspectives

- The validated model will be used for two purposes:
 - 1) design of future lab-scale experiments in the form of perturbations in the operation
 - 2) for predicting the process performance, which is important in future optimization and process control applications and in up-scaling of the system

Process optimization (based on results from Vangsgaard et al., 2012)



Analysis on calibrated model



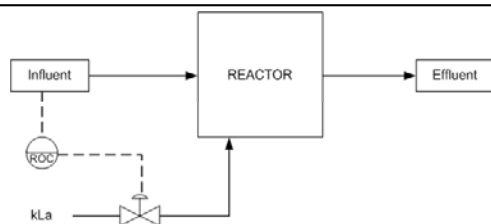
Perspectives

- 2) for predicting the process performance, which is important in future optimization and process control applications and in up-scaling of the system

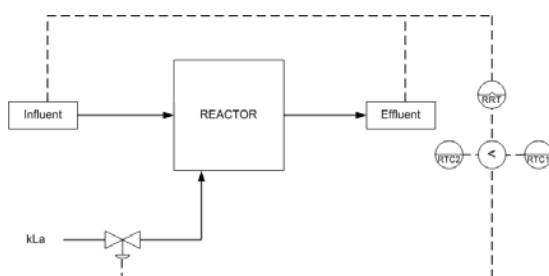
Control implementation:

Three different control strategies have been developed and analyzed on the calibrated model.

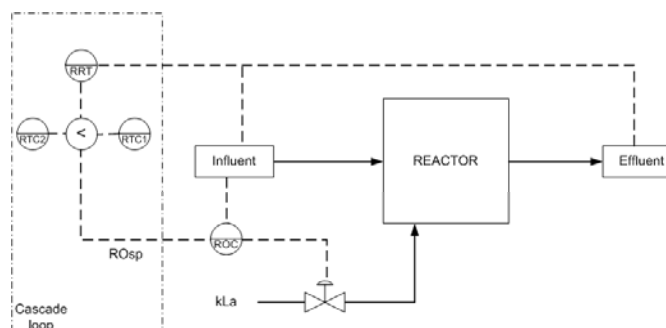
1. Feedforward based on oxygen/nitrogen loading ratio (Vangsgaard et al., 2012)



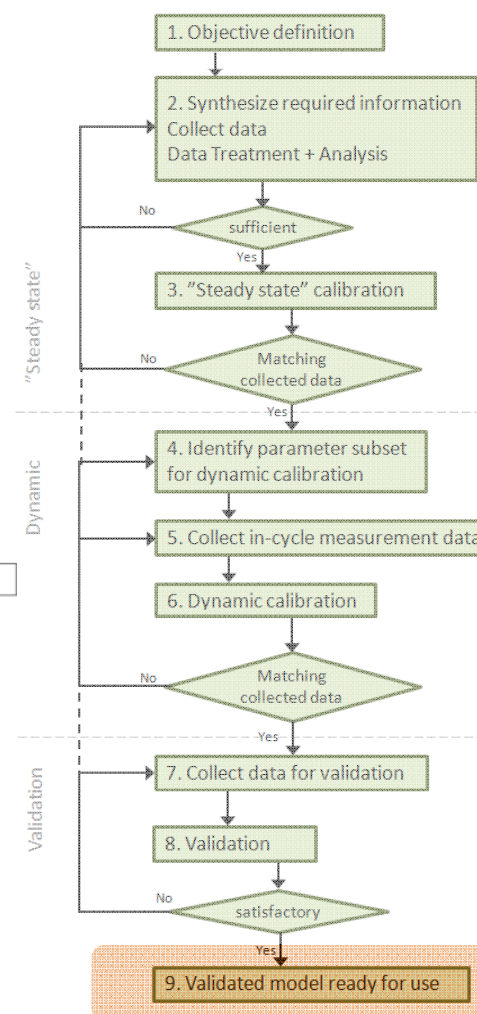
2. Feedforward + feedback based on stoichiometric rules (Mutlu et al., 2012):



3. Cascade control as a combination of 1. and 2.

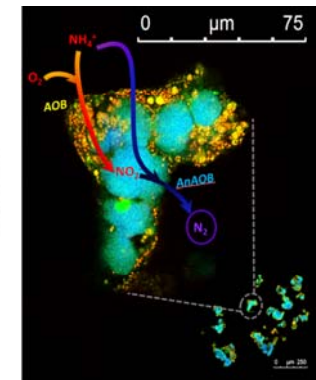
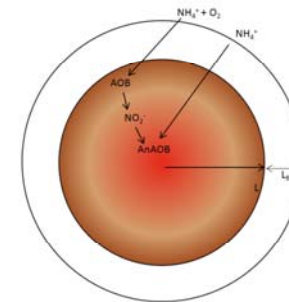


As future extension of the current work, the developed control strategy will be experimentally tested in the lab-scale reactors.



Conclusions/wrap-up

- The model was successfully calibrated and validated by following a developed methodology:
 - First, $k_L a$ was calibrated to long term "steady state" data by using novel evaluation criteria of **stoichiometric ratios** indicating the relative activity of the microbial groups.
 - Second, a subset of parameters were calibrated through dynamic calibration to in-cycle data.
 - An iteration of the second step was performed before a satisfactory result was obtained.
- A fast and efficient novel **initialization process** was developed
 - Simulating 1000 days of continuous operation before SBR operation.
- The model is now being used for optimization and control structure analyses.



Thanks for your attention!

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Contact info:

E-mail: akv@kt.dtu.dk

Phone: +45 45252910

